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(54) **SERIAL LINK RECEIVER WITH IMPROVED BANDWIDTH AND ACCURATE EYE MONITOR**

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See application file for complete search history.

(71) Applicant: **Rambus Inc.**, Sunnyvale, CA (US)

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(72) Inventors: **Marko Aleksić**, Mountain View, CA (US); **Pravin Kumar Venkatesan**, Fremont, CA (US); **Simon Li**, Cupertino, CA (US); **Nikhil Vaidya**, Fremont, CA (US)

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(73) Assignee: **RAMBUS INC.**, Sunnyvale, CA (US)

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*Primary Examiner* — Lihong Yu

(74) *Attorney, Agent, or Firm* — Fenwick & West LLP

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(57) **ABSTRACT**

A receiver includes a decision circuit, a circuit to adjust an input signal of the decision circuit, a correction circuit and a control circuit. The decision circuit makes a data decision based on an input signal of the decision circuit. The circuit to adjust the input signal of the decision circuit adjusts the input signal of the decision circuit based on an input correction signal. The correction circuit combines a plurality of signals corresponding to different input correction parameters into a preliminary input correction signal. An input of the correction circuit is coupled to an output of the decision circuit. The control circuit maps the preliminary input correction signal into the input correction signal using a non-linear code mapping.

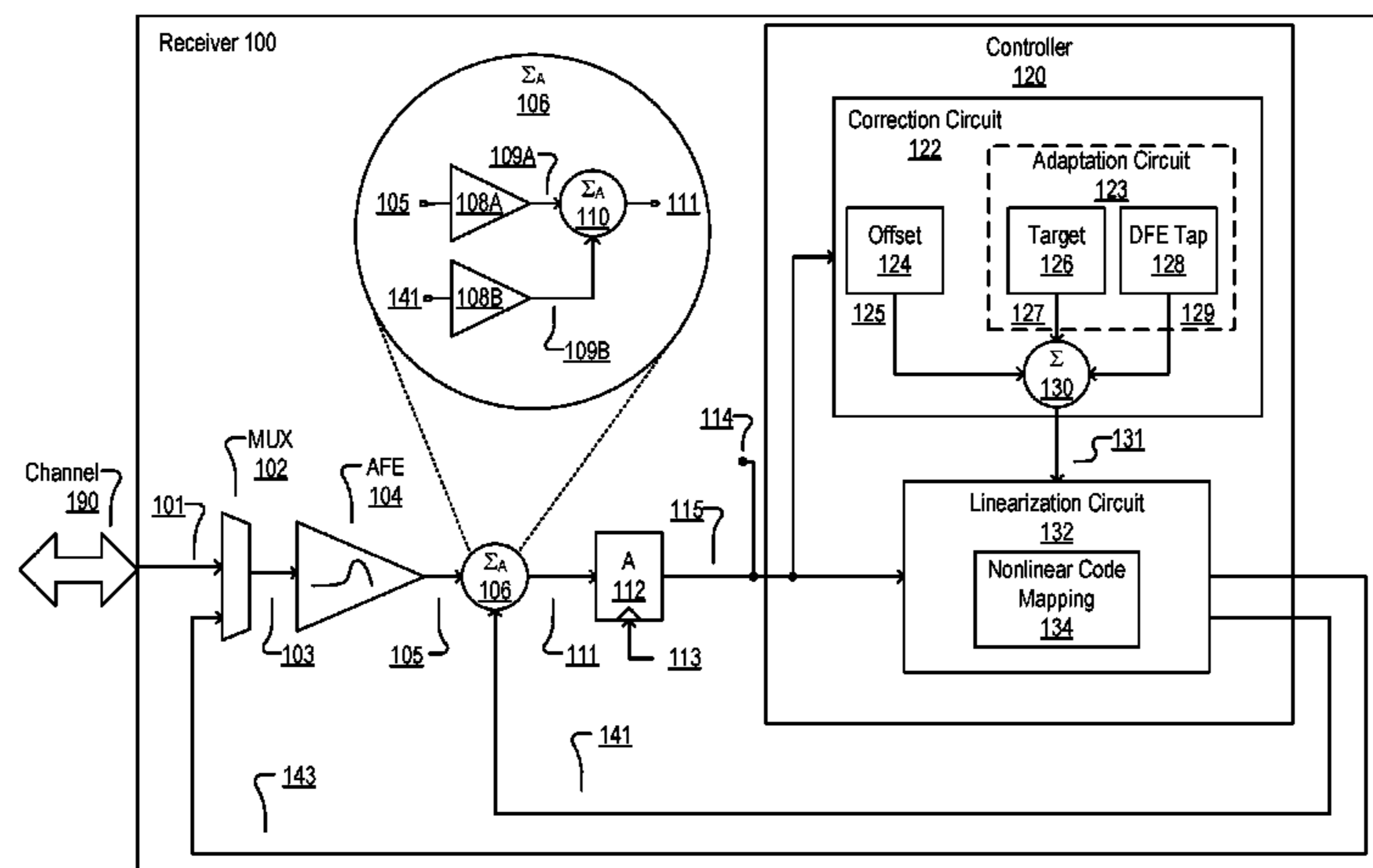
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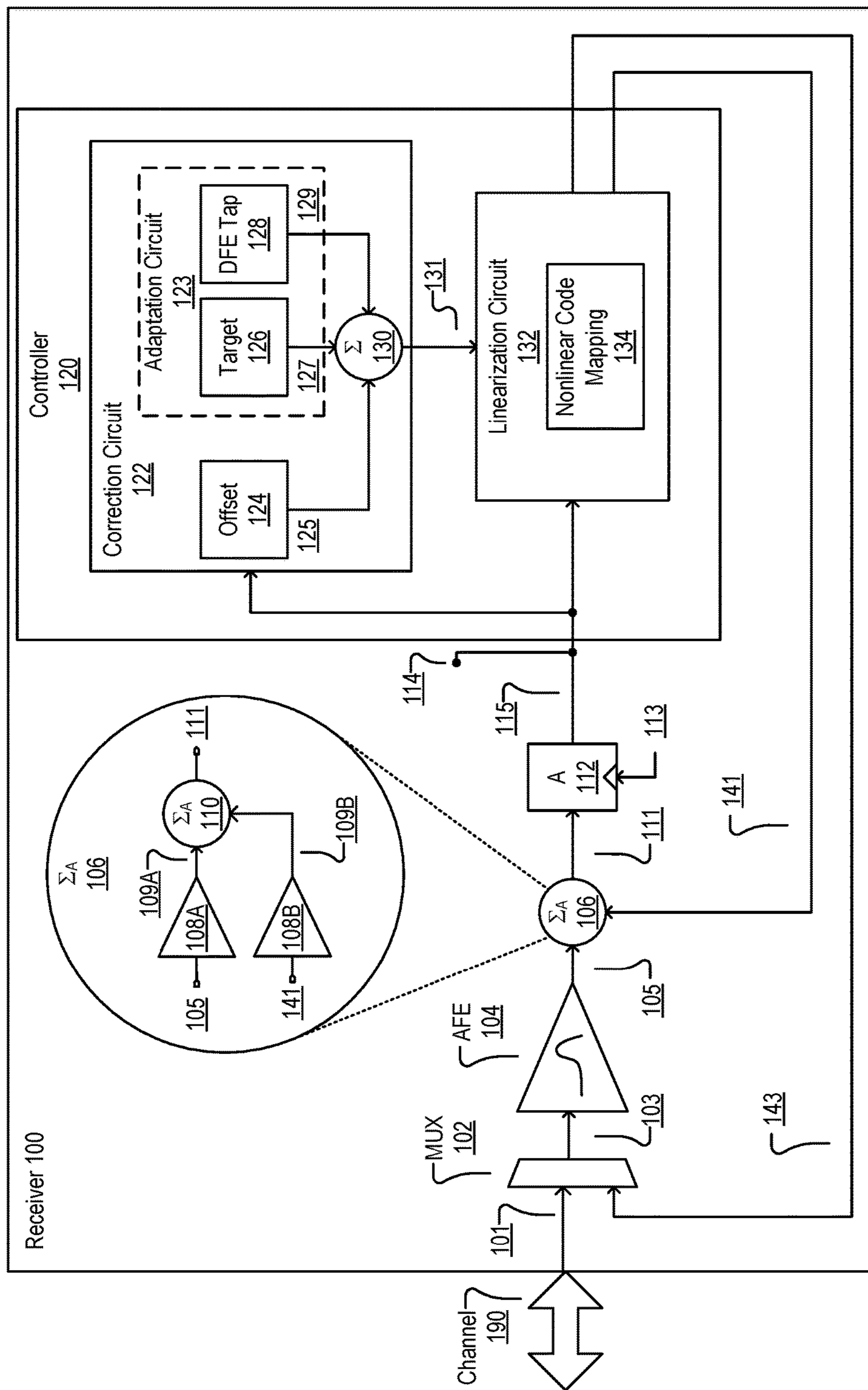


FIG. 1

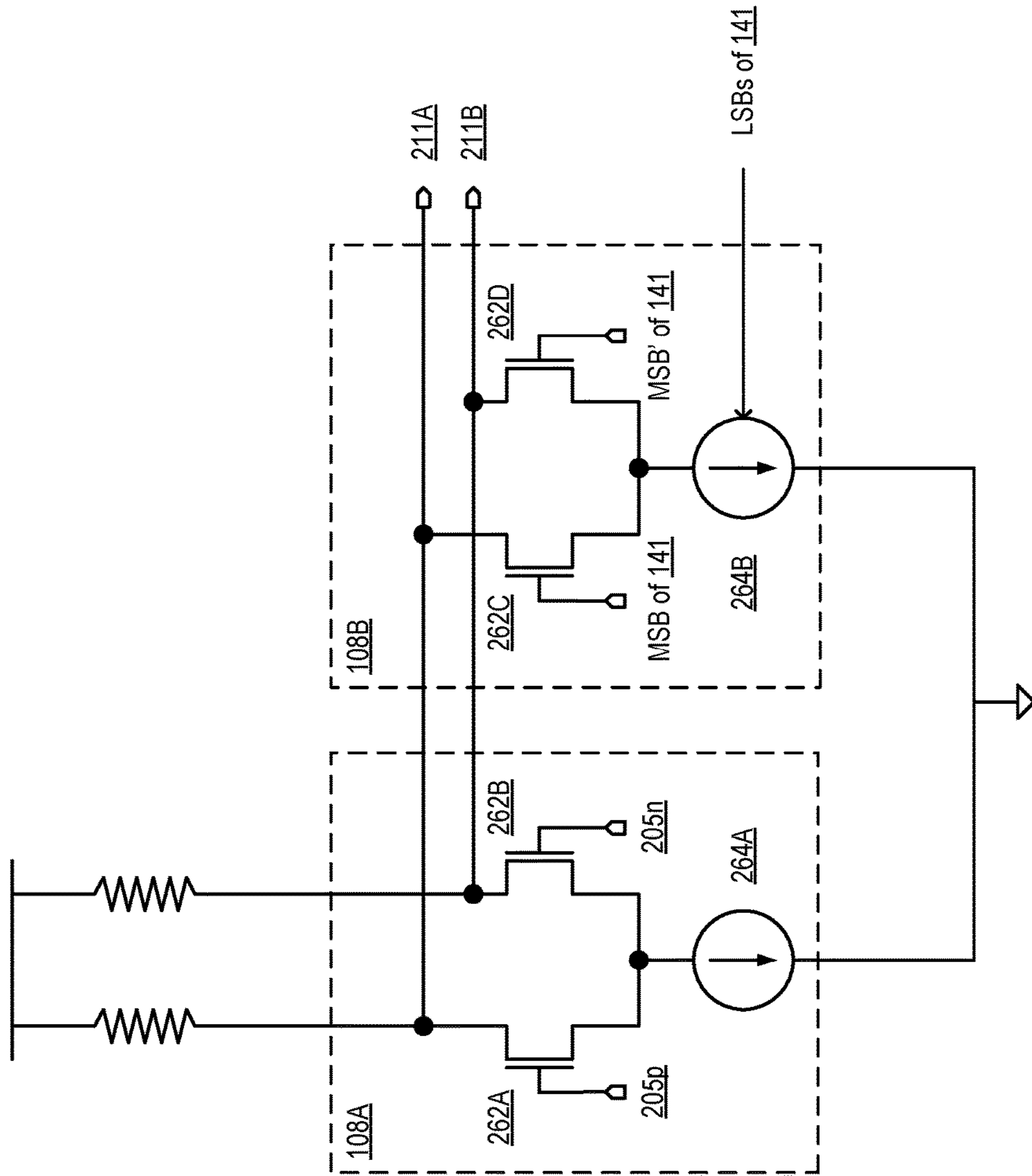


FIG. 2

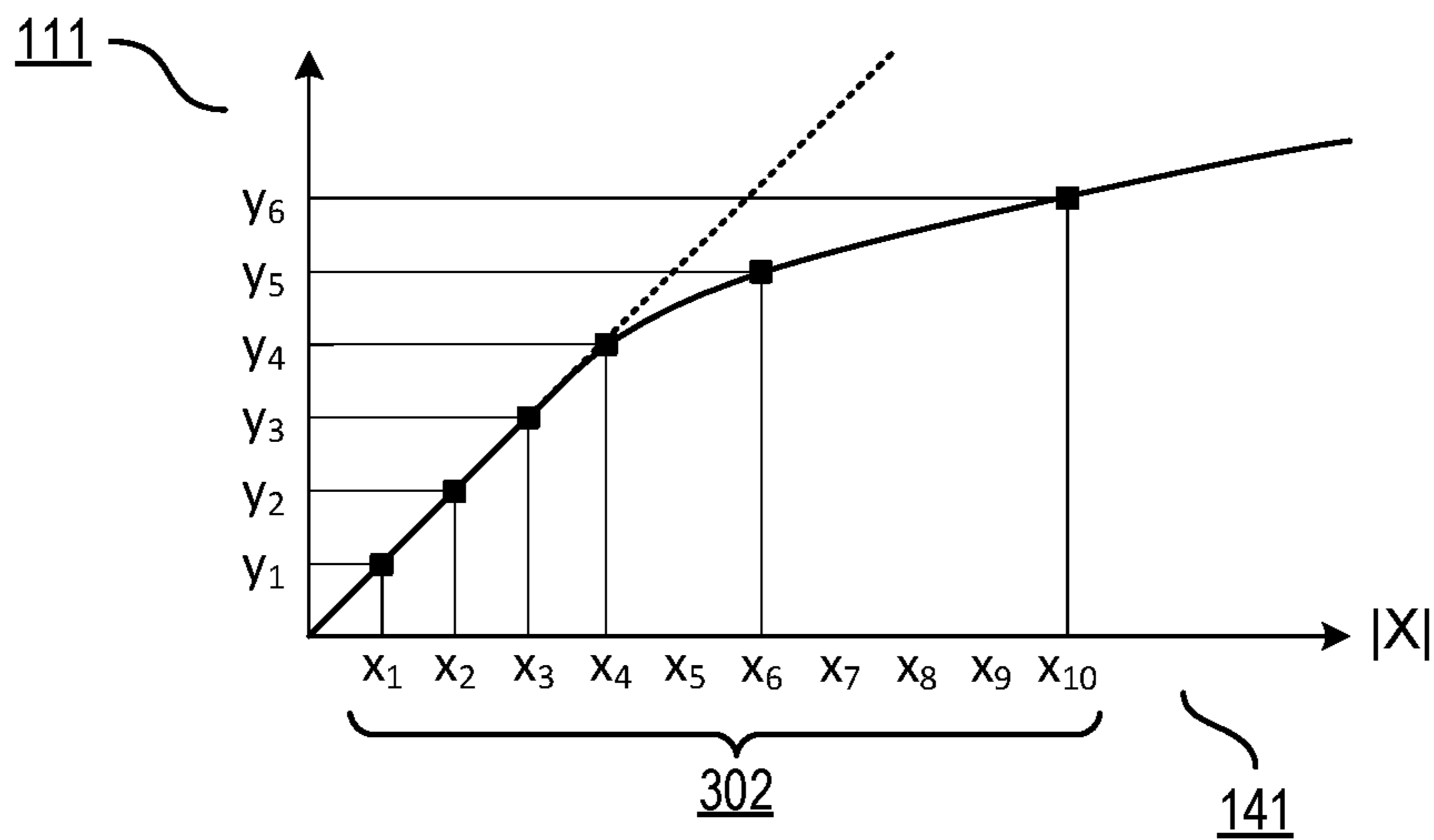


FIG. 3A

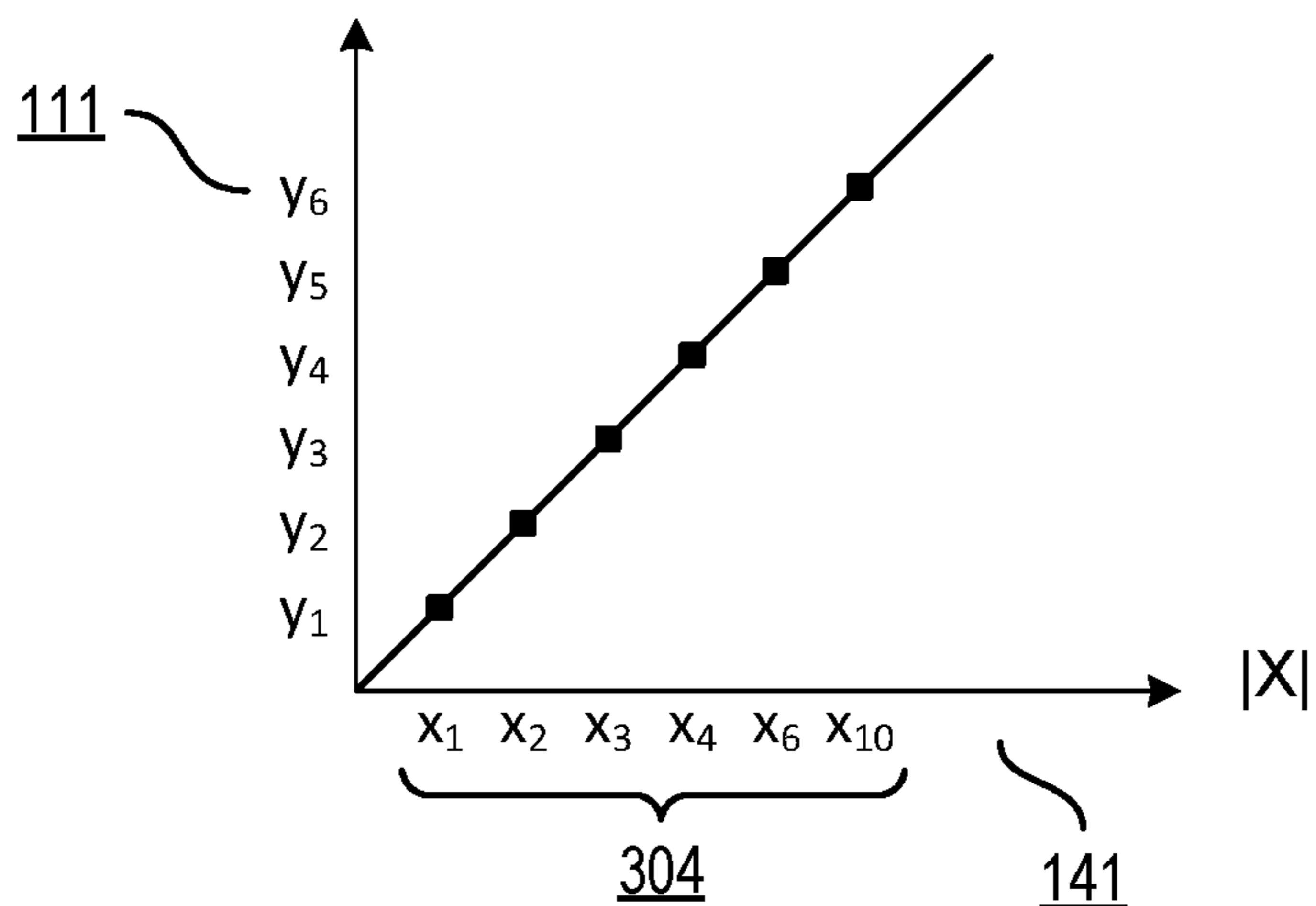
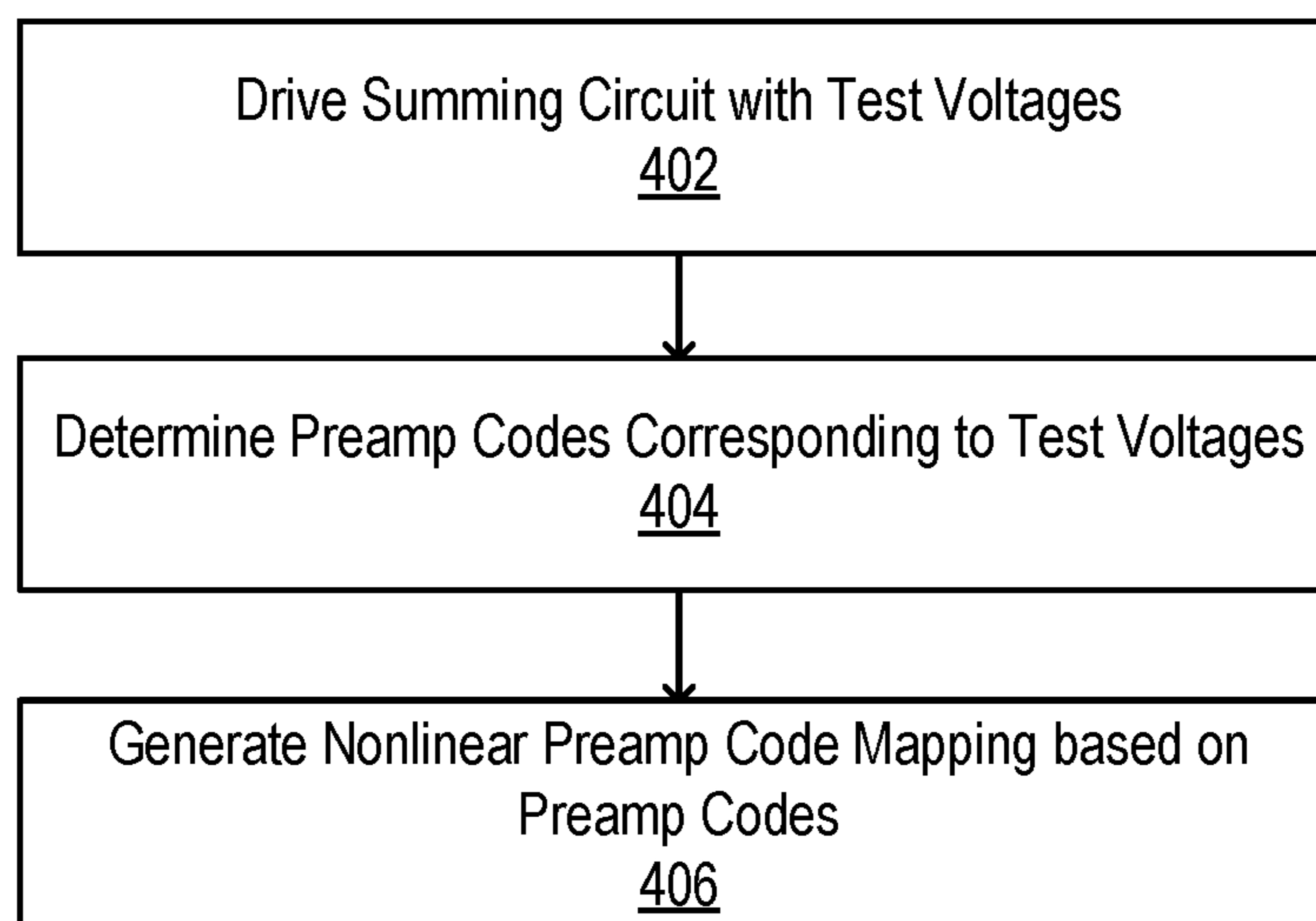
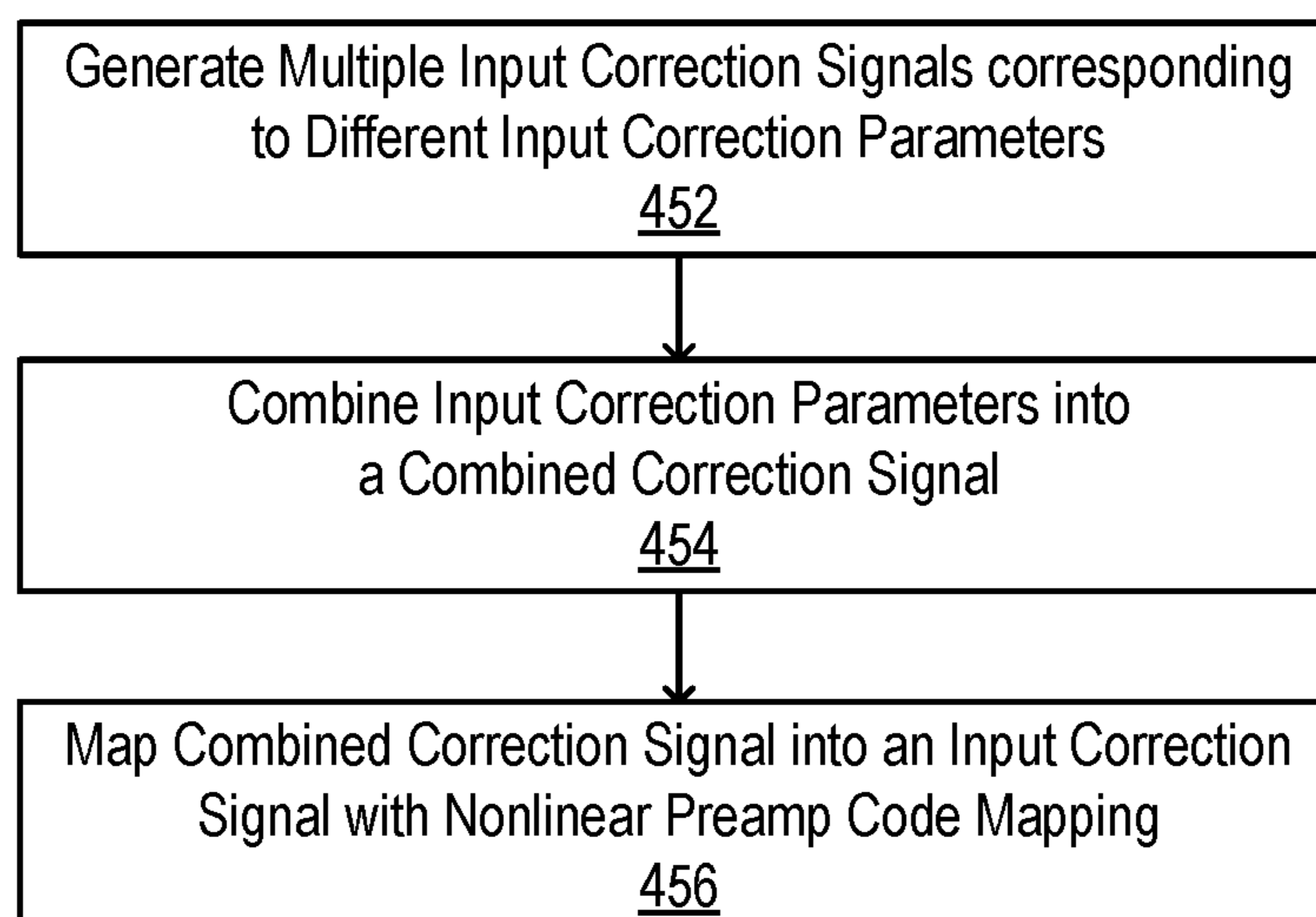


FIG. 3B

**FIG. 4A****FIG. 4B**

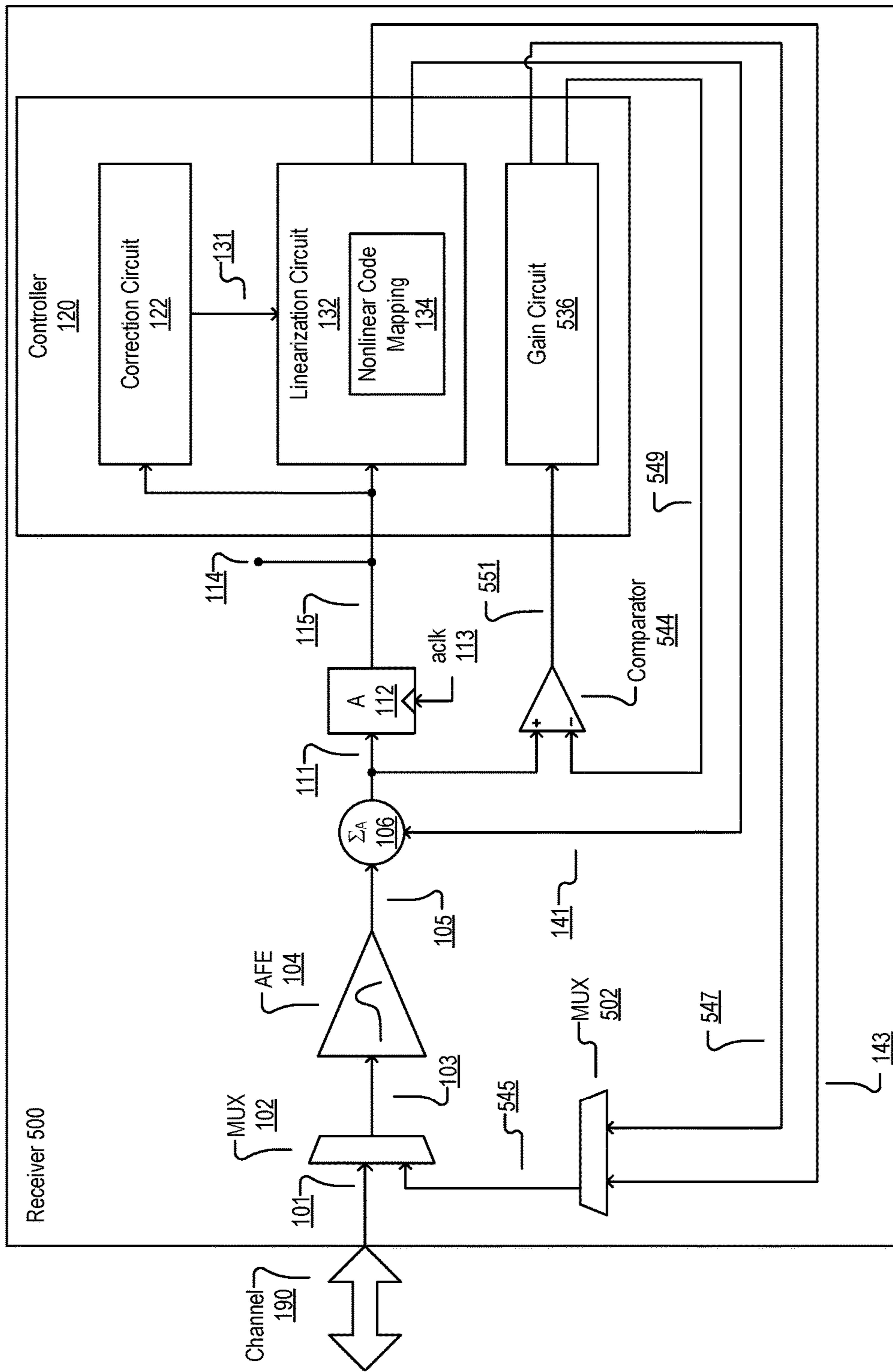
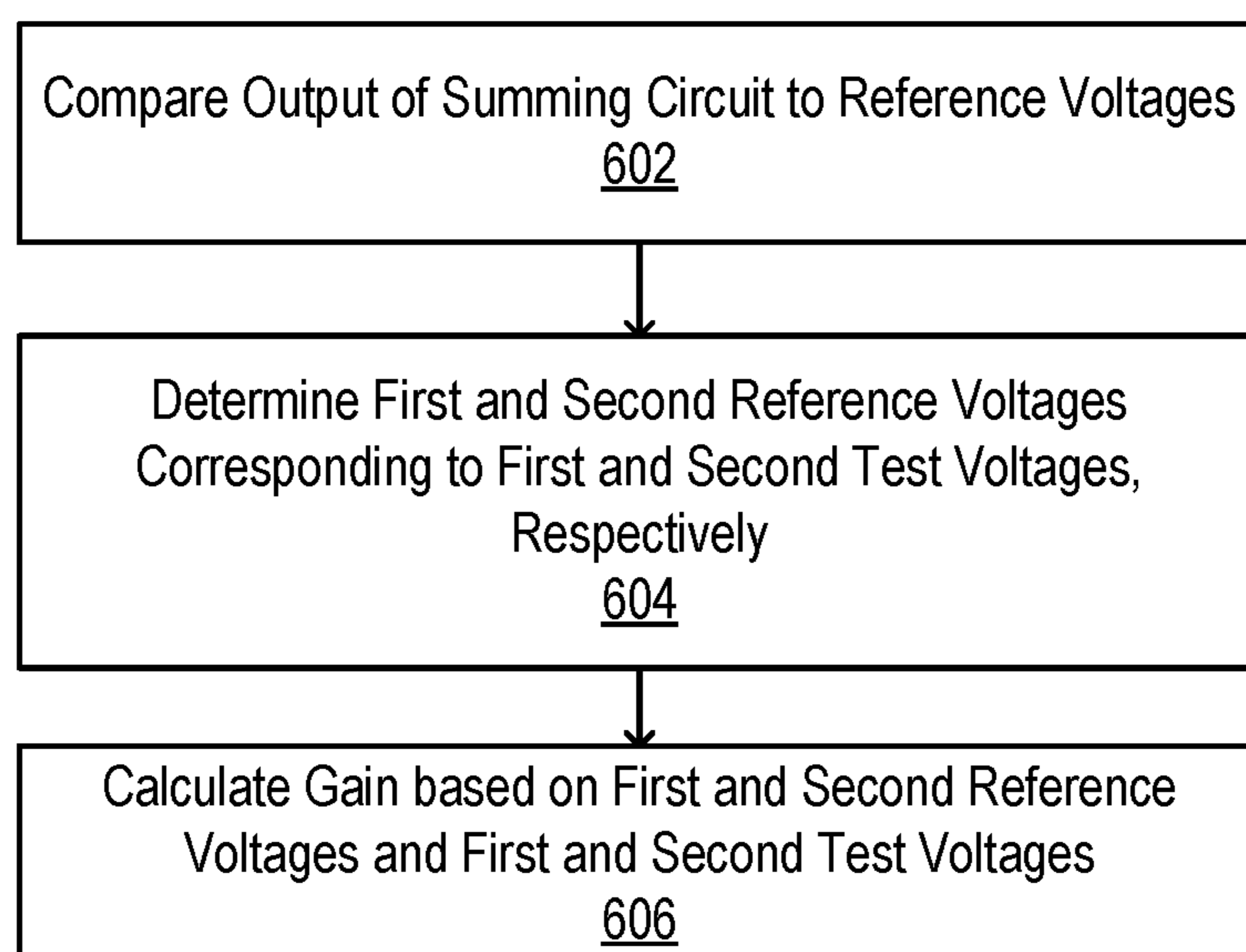


FIG. 5

**FIG. 6**



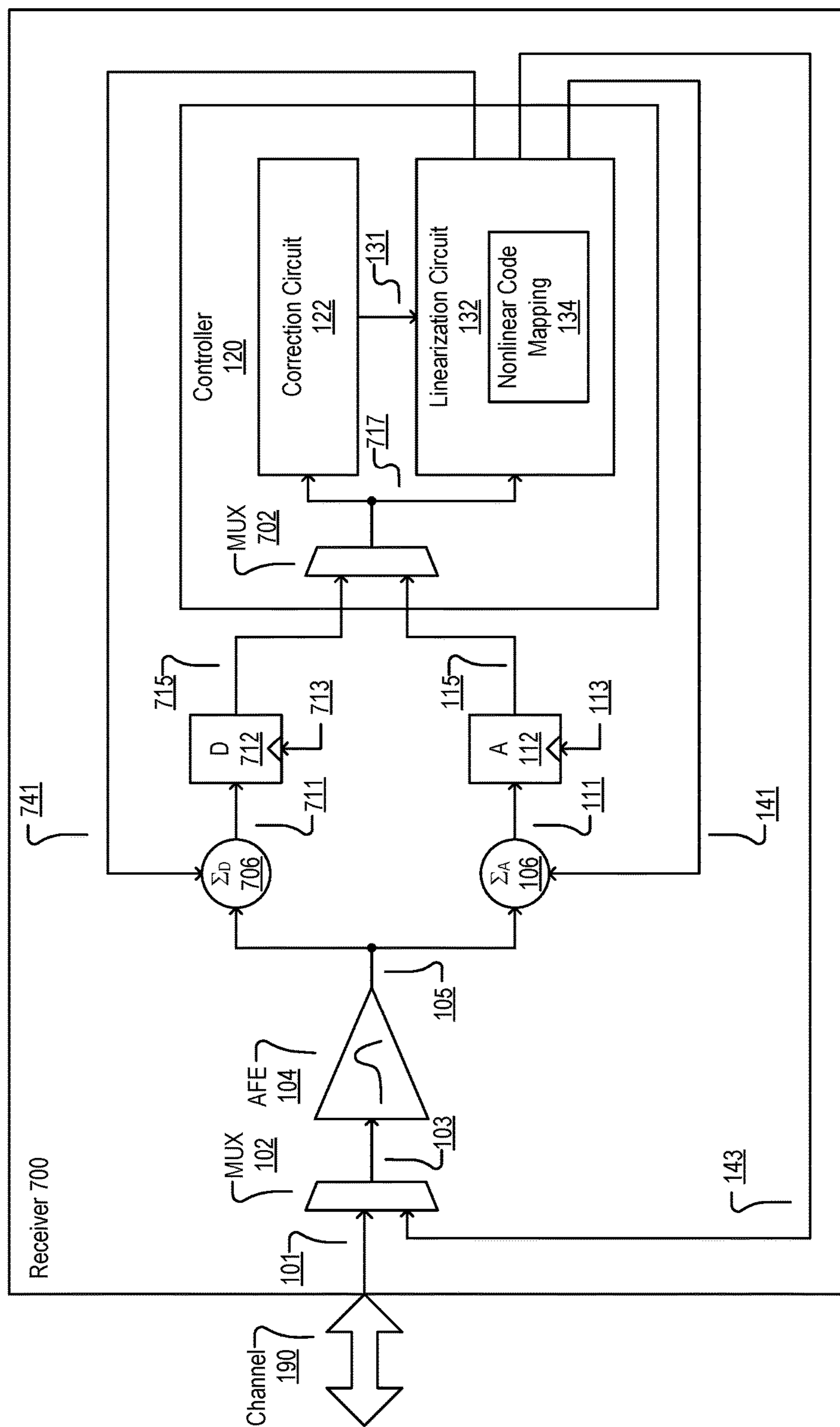


FIG. 7

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## SERIAL LINK RECEIVER WITH IMPROVED BANDWIDTH AND ACCURATE EYE MONITOR

### CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority from U.S. Provisional Patent Application No. 62/301,549 filed on Feb. 29, 2016, the contents of which are incorporated by reference herein in their entirety.

### BACKGROUND

It is desirable for data communication systems to increase data bandwidth so that more data can be transmitted from a transmitter to a receiver in a short amount of time. However, as data bandwidth requirements increase, it becomes increasingly more challenging for the receiver to recover data from the incoming data stream without errors.

### BRIEF DESCRIPTION OF THE DRAWINGS

The disclosed embodiments have advantages and features that will be more readily apparent from the detailed description, the appended claims, and the accompanying figures (or drawings). A brief introduction of the figures is below.

FIG. 1 is a high speed communication system that includes a receiver, according to a one embodiment.

FIG. 2 is an example implementation of a summing circuit, according to one embodiment.

FIG. 3A illustrates a relationship between preamp codes and a corrected input signal, according to one embodiment.

FIG. 3B illustrates a relationship between mapped preamp codes and a corrected input signal, according to one embodiment.

FIG. 4A is a flowchart for generating a nonlinear preamp code mapping during calibration mode, according to one embodiment.

FIG. 4B is a flowchart for mapping the combined correction signal into a mapped preamp code, according to one embodiment.

FIG. 5 is a high speed communication system that includes a receiver, according to another embodiment.

FIG. 6 is a flow chart for calculating a gain, according to one embodiment.

FIG. 7 is a high speed communication system that includes a receiver, according to yet another embodiment.

### DETAILED DESCRIPTION OF EMBODIMENTS

Reference will now be made in detail to several embodiments of the present disclosure, examples of which are illustrated in the accompanying figures. It is noted that wherever practicable similar or like reference numbers may be used in the figures and may indicate similar or like functionality. The figures depict embodiments of the present disclosure for purposes of illustration only. One skilled in the art will readily recognize from the following description that alternative embodiments of the structures and methods illustrated herein may be employed without departing from the principles, or benefits touted, of the disclosure described herein.

In one embodiment, a receiver includes a decision circuit, a circuit to adjust an input signal of the decision circuit, a correction circuit and a control circuit. The decision circuit makes a data decision based on an input signal of the

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decision circuit. The circuit to adjust the input signal of the decision circuit adjusts the input signal of the decision circuit based on an input correction signal. The correction circuit combines a plurality of signals corresponding to different input correction parameters into a preliminary input correction signal. An output of the decision circuit is coupled to an input of the correction circuit. The control circuit maps the preliminary input correction signal into the actual input correction signal using a nonlinear code mapping.

In another embodiment, the receiver includes a summing circuit, a decision circuit, circuitry to drive a set of test voltages, circuitry to determine a plurality of preamp codes, and circuitry to generate a nonlinear preamp code mapping. The summing circuit includes a preamp having nonlinear characteristics. The decision circuit has an input coupled to an output of the summing circuit. The circuitry to drive the set of test voltages drives the set of test voltages at the input of the summing circuit. The circuitry to determine the plurality of preamp codes determines the plurality of preamp codes corresponding to the test voltages based on an output of the decision circuit. The circuitry to generate the nonlinear preamp code mapping generates the nonlinear preamp code mapping based on the plurality of preamp codes. The nonlinear preamp code mapping corrects for the nonlinear characteristics of the preamp to make the preamp response linear.

FIG. 1 is a high speed communication system that includes a receiver **100**, according to one embodiment. The receiver **100** is coupled to a wired or wireless communication channel **190** and receives an analog channel signal **101** from a remote transmitter (not shown) through the wired or wireless communication channel **190**. The analog channel signal **101** carries single ended or differential signals.

The analog channel signal **101** is generated at the transmitter from digital data. The receiver **100** recovers an output data signal **115** at an output node **114** from the analog channel signal **101**. The output node **114** can be coupled to components of the receiver **100** not illustrated in FIG. 1. In some embodiments, the receiver **100** can be a standalone device or part of a larger device, such as an application specific integrated circuit (ASIC). The receiver **100** includes a multiplexer (MUX) **102**, an analog front end (AFE) **104**, a summing preamp circuit ( $\Sigma_A$ ) **106**, a data decision circuit (A) **112**, and a controller **120**. Each of these components can be implemented with hardware circuits that generate signals, and the lines connecting the components carry signals from one component to the next.

The receiver **100** can operate in two modes: a calibration mode and a normal operating mode. In the calibration mode, the controller **120** generates a nonlinear preamp code mapping that corrects for nonlinear characteristics of the summing preamp circuit **106**. In the normal operating mode, the controller **120** adjusts a preamp code provided to the summing preamp circuit **106** based on the generated nonlinear preamp code mapping.

The MUX **102** receives the analog channel signal **101** and a test voltage signal **143** and selects one of the analog channel signal **101** and the test voltage signal **143** for its output, selected signal **103**. In the calibration mode, the MUX **102** selects the test voltage signal **143**, and in the normal operating mode, the MUX **102** selects the analog channel signal **101**.

The input of the AFE **104** is coupled to the output of the MUX **102**. The AFE **104** performs pre-processing of the selected signal **103** to generate an analog input signal **105**. The analog channel signal **101** can be non-ideal due to channel impairments, such as insertion loss, crosstalk, inter

symbol interference and optical dispersion. The AFE 104 uses analog processing to reduce some of these non-idealities. Examples of analog processing techniques include gain adjustment or continuous time equalization filters. In other embodiments, the AFE 104 can simply be an input terminal that receives the selected signal 103 and passes it on to generate the analog input signal 105 with no signal processing.

The summing preamp circuit 106 receives the analog input signal 105 from the AFE 104 and an input correction signal 141 from the controller 120, buffers the analog input signal 105, converts the input correction signal 141 into an analog signal and then combines the buffered analog input signal and the converted input correction signal to generate a corrected input signal 111. The input correction signal 141 is a digital signal that includes multi-bit digital codes and provides feedback for adjusting a voltage level of the corrected input signal 111.

Unlike in the summing preamp circuit 106 illustrated in FIG. 1 that receives a single correction signal 141, the summing preamp circuit 106 traditionally receives an analog offset correction signal, an analog target signal, and an analog decision feedback equalizer (DFE) tap signal. The summing preamp circuit 106 traditionally includes a main preamp to buffer the analog input signal 105, and can also include a second preamp to convert an offset correction signal to the analog offset correction signal, a third preamp to convert a target voltage signal to the analog target voltage signal, and a fourth preamp to convert a DFE tap signal to the analog DFE tap signal. The summing preamp circuit 106 traditionally including separate second through fourth preamps ensures that responses of the second through fourth preamps (i.e., the analog signals output from the second through fourth preamps) are linear. However, including the second through fourth preamps causes bandwidth limitations when the analog signals output from the second through fourth preamps are combined with the buffered analog signal output from the main preamp. The bandwidth limitations can be, for example, due to parasitic loading from the second through fourth preamps.

To overcome the bandwidth limitations, the previously described second through fourth preamps in the summing preamp circuit 106 are combined into a single correction preamp. The single correction preamp is used to convert an input correction signal representing a combination of the offset correction signal, the target voltage signal and the DFE tap signal into a corrected analog signal. Although replacing multiple preamps (i.e., the second through fourth preamps) with a single correction preamp does create non-linearity which is compensated for by use of a nonlinear code mapping as described below.

As shown in FIG. 1, the summing preamp circuit 106 according to an embodiment of the present disclosure includes a main preamp 108A, a correction preamp 108B and a summing node ( $\Sigma_A$ ) 110. The main preamp 108A has linear characteristics whereas the correction preamp 108B has nonlinear characteristics. If left uncorrected, the nonlinear characteristics of the correction preamp 108B can lead to an undesired amount of correction to the corrected input signal 111. In addition, if shmooring of the corrected input signal 111 is performed using the data decision circuit 112 (or another detection circuit whose input is coupled to the corrected input signal 111) in conjunction with the summing preamp circuit 106, the nonlinear response of the correction preamp 108B can lead to inaccurate eye monitor measurements, specifically, an inaccurate estimate of a vertical eye opening. The main preamp 108A receives the analog input

signal 105 and buffers the analog input signal 105 into a buffered signal 109A. Correction preamp 108B is implemented as a digital to analog converter (DAC). The correction preamp 108B receives the input correction signal 141 and converts the input correction signal 141 into an analog correction signal 109B. The analog correction signal 109B is an analog representation of the digital input correction signal 141. The summing node 110 receives the buffered signal 109A and the analog correction signal 109B and combines the two inputs to generate the corrected input signal 111.

Additionally, signals 101, 103, 105 and 111 are typically differential signals, although they are shown only with single lines in FIG. 1. In other embodiments these and other signals within the receiver 100 may be either differential or single ended, depending on the embodiment.

Referring briefly to FIG. 2, it illustrates an implementation of the summing preamp circuit 106, according to one embodiment. The main preamp 108A includes first and second transistors 262A-B and current source 264A. The first transistor 262A is controlled by a positive differential analog input signal 205<sub>p</sub> and the second transistor 262B is controlled by a negative differential analog input signal 205<sub>n</sub>. In one embodiment, the positive and negative differential analog signals 205<sub>p</sub> and 205<sub>n</sub> are positive and negative differential signals of the analog input signal 105. In one embodiment, the current source 264A is not controlled by any of the signals of FIG. 1. In this embodiment, the current source 264A can be a fixed current source. The main preamp 108A has substantially linear gain.

Similarly, the correction preamp 108B includes third and fourth transistors 262C-D and digitally controlled current source 264B. The multi-bit digital codes of the input correction signal 141 include a most significant bit (MSB) and one or more least significant bits (LSBs). The LSBs of the multi-bit digital codes of the input correction signal 141 control the level of current sunk by the current source 264B. The current sunk by the current source 264B can be referred to as tail current.

The MSB of the multi-bit digital codes of the input correction signal 141 controls which transistor 262C and 262D is turned on and is provided with the current. The third transistor 262C is controlled by the MSB of the multi-bit digital code of the input correction signal 141 and the fourth transistor 262D is controlled by an inverted value of the MSB (MSB') of the multi-bit digital code of the input correction signal 141.

The structure of the correction preamp 108B causes the correction preamp 108B to have nonlinear digital to analog conversion characteristics. In other words, the relationship between input correction signal 141 and the analog correction signal 109B is not a linear relationship. Instead, this relationship is nonlinear.

Referring back to FIG. 1, the data decision circuit 112 receives the corrected input signal 111 and makes a data decision on the logical data value represented by the voltage of corrected input signal 111. The data decision circuit 112 then generates the output data signal 115 that represents the data decision. The output data signal 115 can be a binary signal.

The data decision circuit 112 is controlled by its own sampling clock signal 113. The data decision circuit 112 generates the output data signal 115 at the phase of the sampling clock signal 113. In one embodiment, the data decision circuit 112 includes a comparator that compares the positive and negative differential portions of the corrected input signal 111 to each other, and generates the output data signal 115 from this comparison.

In one embodiment, the signal path from MUX 102 to the corrected input signal 111 represents a primary signaling path through the receiver 100. The signal path from controller 120 through input correction signal 141 and preamp 108B represents a feedback correction path through the receiver 100.

The controller 120 receives the output data signal 115 and generates the test voltage signal 143 and the input correction signal 141. In the calibration mode, the controller 120 generates a nonlinear preamp code mapping 134 that accounts for the nonlinear characteristics of the correction preamp 108B. In the normal operating mode, the controller 120 generates mapped preamp codes using the nonlinear preamp code mapping 134. The controller 120 includes a correction circuit 122 and a linearization circuit 132.

In the calibration mode, the linearization circuit 132 receives the output data signal 115 and generates the nonlinear preamp code mapping 134 that accounts for the nonlinear characteristics of the correction preamp 108B. The code mapping 134 can be stored in a look up table (LUT) or in the form of an equation. The operation of the linearization circuit 132 is now explained in greater detail by reference to FIG. 3A-3B.

Referring briefly to FIG. 3A, it illustrates a magnitude of a voltage of the corrected input signal 111 as a function of a magnitude of the input correction signal 141. The relationship between the input correction signal 141 and the analog correction signal 109B observed at the corrected input signal 111 is not a linear relationship. That is, as the values of the input correction signal 141 increases in fixed increments, the voltage of the corrected input signal 111 increases in a nonlinear manner.

Specifically, the X-axis represents absolute values of a full set of preamp codes 302 that can be output via the input correction signal 141. The Y-axis represents absolute values of voltages of the corrected input signal 111. To correct for the nonlinear relationship between preamp codes 302 and voltages of the corrected input signal 111, the linearization circuit 132 attempts to identify a subset of the full set of preamp codes 302 that result in a linear relationship to the voltages of the corrected input signal 111.

The initial full set 302 represents all possible preamp codes the linearization circuit 132 can output as values of the input correction signal 141. As illustrated in FIG. 3A, the initial full set 302 includes preamp codes  $x_1$  through  $x_{10}$ . The linearization circuit 132 determines a preamp code (e.g.,  $x_1$ ) of the initial full set 302 which cancels out a voltage (e.g.,  $y_1$ ) and causes the output data signal 115 to change values. The linearization circuit 132 repeats this process for 'n' test voltages at the test voltage signals 143, which result in 'n' corrected voltages at the corrected input signal 111, and determines 'n' preamp codes of the initial full set 302. Each of the determined 'n' preamp codes of the initial full set 302 corresponds to a test voltage at the test voltage signal 143 based on a corrected voltage at the corrected input signal 111.

Specifically, the linearization circuit 132 outputs a test voltage at the test voltage signal 143 which results in a corrected voltage (e.g.,  $y_1$ ) at the corrected input signal 111. The linearization circuit 132 varies the value of the input correction signal 141 by varying (i.e., sweeping) preamp codes of an initial full set of preamp codes 302 while monitoring the output data signal 115. The linearization circuit 132 varies the value of the input correction signal 141 until the corrected input signal 111 reaches zero volts. Once the corrected input signal 111 reaches zero volts, the output data signal 115 changes values (e.g., from 1 to 0). The

preamp code 302 that caused the output data signal 115 to change values is added to the subset.

Successive test voltages at the test voltage signal 143 result in successive corrected voltages (i.e.,  $y_1$  through  $y_6$ ) at the corrected input signal 111. The successive corrected voltages at the corrected input signal 111 are equidistant. Similarly, successive preamp codes of the initial full set of preamp codes 302 are also equidistant. However, not every preamp code of the initial full set 302 corresponds to a test voltage of the test voltage signal 143 based on a corrected voltage at the corrected input signal 111. For example, preamp code  $x_5$  and preamp codes  $x_7$  through  $x_9$  of the initial full set 302 do not correspond to a corrected voltage at the corrected input signal 111. Thus, there is a nonlinear relationship between the initial full set of preamp codes 302 and the corrected voltages of the corrected input signal 111.

To correct the nonlinear relationship, the linearization circuit 132 generates a nonlinear preamp code mapping 134 based on a subset of preamp codes of the initial full set of preamp codes 302 that correspond to corrected voltages at the corrected input signal 111. As illustrated in FIG. 3B, the subset of preamp codes 304 includes  $x_1$  through  $x_4$ ,  $x_6$ , and  $x_{10}$ . The reduced set 304 is determined from the initial full set 302. The reduced set 304 does not include preamp codes of the initial full set 302 that do not correspond to a corrected voltage at the corrected input signal 111. For example, preamp code  $x_5$  and preamp codes  $x_7$  through  $x_9$  of the initial full set 302 are not included in the reduced set 304. Providing only the reduced set of preamp codes 304 to the preamp 108B results in a linear relationship with the corrected input signal 111.

In one embodiment, the nonlinear code mapping 134 can be generated as a look up table that maps input codes to output codes. The table can be similar to this table:

Input code	Mapped Code
$x_1$	$x_1$
$x_2$	$x_2$
$x_3$	$x_3$
$x_4$	$x_4$
$x_5$	$x_6$
$x_6$	$x_{10}$

In other embodiments, the nonlinear preamp code mapping 134 can be generated in the form of a formula. In other embodiments, the nonlinear preamp code mapping 134 may be generated in other forms.

In the normal operating mode, the linearization circuit 132 receives a combined correction signal 131 from the correction circuit 122, maps the combined correction signal 131 into a mapped preamp code of the reduced set 304 using the nonlinear preamp code mapping 134, and generates the input correction signal 141 with the mapped preamp code. In one example, the combined correction signal 131 represents a desired amount of voltage correction at the corrected input signal 111. In this example, the linearization circuit 132 maps the combined correction signal 131 to a preamp code of the reduced set of preamp codes 304 using the nonlinear preamp code mapping 134.

Referring back to FIG. 1, the correction circuit 122 receives the output data signal 115 and generates the combined correction signal 131. The correction circuit 122 includes an offset correction circuit 124, an adaptation circuit 123, and a parameter summing circuit 130. The adaptation circuit 123 includes an adaptation target circuit 126 and a DFE tap circuit 128.

In the normal operating mode, the offset correction circuit **124** generates an offset correction signal **125**, the adaption circuit **123** generates a target voltage signal **127** and a DFE tap signal **129**. Specifically, the adaptation target circuit **126** generates the target voltage signal **127** and the DFE tap circuit **128** generates the DFE tap signal **129**. Each of signals **125**, **127** and **129** represent a different correction parameter that is used to correct for a different signaling problem. The parameter summing circuit **130** combines the offset correction signal **125**, the target voltage signal **127**, and the DFE tap signal **129** to generate the combined correction signal **131**. In one example, the combined correction signal **131** represents a target amount of correction to apply to the corrected input signal **111**.

As mentioned previously, combining the offset correction signal **125**, the target voltage signal **127**, and the DFE tap signal **129** leads to bandwidth improvements in the receiver **100**. This is because, instead of having separate preamps in the summing preamp circuit **106** for each correction parameter signal, only a single preamp **108B** can be used to apply all three correction parameters to the corrected input signal **111**. As a result, the capacitive load at the input to the decision circuit **112** can be decreased. Although replacing multiple preamps with a single preamp **108B** does create non-linearity in the preamp **108B**, the non-linearity is compensated for by use of the nonlinear code mapping **134**.

The offset correction circuit **124** generates the offset correction signal **125** representing a target amount of voltage compensation needed to compensate for a direct current (DC) offset between the positive and negative differential inputs of the data decision circuit **112** (i.e., the corrected input signal **111**). The DC offset of the data decision circuit **112** is an inherent and unwanted characteristic of the data decision circuit **112**. The offset correction circuit **124** can use the output data signal **115** and certain offset cancellation algorithms to determine an amount of offset correction needed to cancel out this unwanted offset.

The adaptation circuit **123** tries to find a set of TX and RX (CTLE+VGA+DFE) coefficients to minimize channel intersymbol interference (ISI) and hence improve signal quality. A typical algorithm that is used is the sign-sign LMS (or, SS-LMS). It is an iterative process. In each step, an adaptation algorithm changes the coefficients (e.g., CTLE, VGA, DFE tap values) and observes whether the received signal is below or above some target voltage level, in order to evaluate whether the new coefficient helps or hurts the signal. Conceptually, this is done by comparing the corrected input signal **111** to the target voltage level. In practice, this comparison is done indirectly by applying the target voltage to the input of the data decision circuit **112** via input correction signal **141**, which effectively adjusts the trip threshold of the data decision circuit **112** by introducing an additional voltage at the correction input signal **111** input to the data decision circuit **112**. The amount of voltage introduced at the input of the data decision circuit **112** is equal to the target voltage level for adaptation. Depending on the outcome of the comparison (reflected in output data signal **115**), the coefficients are increased or decreased.

The adaptation target circuit **126** generates an adaptation target voltage signal **127**. The adaptation target voltage signal **127** represents a target voltage level for adaptation of receiver coefficients, as described above. The target voltage signal **127** may only be used during the adaptation process and may otherwise be set to zero. The target voltage signal **127** is set to a level that is used during adaptation to minimize ISI. In one embodiment, the receiver **100** includes a second summing preamp circuit (e.g., summing circuit **706**

in FIG. 7) similar to the summing circuit **106** and a second decision circuit (e.g., decision circuit **712** in FIG. 7) similar to the decision circuit **112** that are used during execution of the adaptation algorithm. In this embodiment, the target signal applied to the second decision circuit can be effectively zero.

The DFE tap circuit **128** generates the DFE tap signal **129**. The DFE tap circuit **128** delays the output data signal **115** by one or more clock cycles, weights the delayed data signal using a DFE tap weight, and then generates a DFE tap signal **129**. The DFE tap signal **129** is thus a delayed and weighted version of the output data signal **115**. The DFE tap weight (i.e. DFE tap coefficient) can be set during the adaption process by the adaptation target circuit **126**. Additionally, the DFE tap circuit **128** may have multiple taps with varying delays and weights that are summed together to generate the DFE tap signal **129**.

FIG. 4A is a flowchart for generating the nonlinear preamp code mapping **134** during calibration mode, according to one embodiment. The linearization circuit **132** drives the summing preamp circuit **106** with a set of equidistant test voltages at the test voltage signal **143**. The set of test voltages at the test voltage signal **143** result in corrected voltages at the corrected input signal **111**. The linearization circuit **132** determines **404** preamp codes corresponding to the test voltages. The linearization module generates **406** a nonlinear preamp code mapping **134** based on the preamp codes.

FIG. 4B is a flowchart for mapping the combined correction signal **131** into a mapped preamp code, according to one embodiment. The correction circuit **122** generates **452** multiple input correction signals corresponding to different input correction parameters. Specifically, the offset correction circuit **124** generates the offset correction signal **125**, the adaptation target circuit **126** generates the adaptation target voltage signal **127**, and the DFE tap circuit **128** generates the DFE tap signal **129**. The parameter summing circuit **130** of the correction circuit **122** combines **454** the input correction parameters (i.e., the offset correction signal **125**, the adaptation target voltage signal **127**, and the DFE tap signal **129**) to generate a combined correction signal **131**. The linearization circuit **132** maps **456** the combined corrected signal **131** into a preamp code of the input correction signal **141** using the nonlinear preamp code mapping **134**.

FIG. 5 is a high speed communication system that includes a receiver **500**, according to another embodiment. The receiver **500** illustrated in FIG. 5 is similar to the receiver **100** illustrated in FIG. 1. The main difference is that the receiver **500** of FIG. 5 includes a MUX **502** and a comparator **544**, and the controller **120** includes a gain circuit **536**.

The receiver **500** of FIG. 5 can operate in three modes: the calibration mode, the normal operating mode, and a gain calculation mode. In the gain calculation mode, the gain circuit **536** calculates a gain of the AFE **104**. The gain of the AFE **104** is used to determine accurate eye monitoring measurements.

The MUX **502** receives the test voltage signal **143** and a test voltage signal **547** and selects one of the test voltage signal **143** and the test voltage signal **547** for its output, selected signal **545**. In the calibration mode, the MUX **502** selects the test voltage signal **143**, and in the gain calculation mode, the MUX **502** selects the test voltage signal **547**.

The comparator **544** receives the corrected input signal **111** (i.e., the output of the summing preamp circuit **106**) and a reference voltage signal **549** and compares the received signals. The comparator **544** outputs a comparison signal

551 indicating whether the corrected input signal 111 is higher/lower than the reference voltage signal 549.

In the gain calculation mode, the gain circuit 536 receives the comparison signal 551 and outputs the test voltage signal 547 and the reference voltage signal 549. The gain circuit 536 calculates a gain of the AFE 104 and the summing preamp circuit 106 based on the reference signal 547, the test voltage signal 547 and the comparison signal 551. In one example, voltages at the test voltage signal 547 and voltages at the reference voltage signal 549 are generated from identical digital-to-analog converters of the gain circuit 536.

The gain circuit 536 outputs a first test voltage at the test voltage signal 547. The gain circuit 536 varies the voltage of the reference voltage signal 549 until the gain circuit 536 determines the comparison signal 551 changes values. The gain circuit 536 determines a first reference voltage of the reference voltage signal 549 at which the comparison signal 551 changed values. The gain circuit 536 then outputs a second test voltage at the test voltage signal 547, varies the voltage of the reference voltage 549 until the comparison signal 551 changes values, and determines a second reference voltage of the reference voltage signal 549 at which the comparison signal 551 changed values.

The gain circuit 536 calculates the gain of the AFE 104 and the summing preamp circuit 106 based on the first and second test voltages and the first and second reference voltages. The gain circuit 536 can calculate the gain of the AFE 104 and the summing preamp circuit 106 based on a quotient of a difference of the first and second reference voltages and a difference of the first and second test voltages. For example, the gain circuit 536 calculates the gain of the AFE 104 and the summing preamp circuit 106 according to equation 1:

$$K = \frac{V_{R2} - V_{R1}}{V_{T2} - V_{T1}} \quad (\text{Equation 1})$$

where K is the gain,  $V_{R2}$  is the second reference voltage,  $V_{R1}$  is the first reference voltage,  $V_{T2}$  is the second test voltage, and  $V_{T1}$  is the first test voltage.

FIG. 6 is a flow chart for calculating a gain, according to one embodiment. The comparator 544 compares 602 the output of the summing preamp circuit 106 (i.e., the corrected input signal 111) to reference voltages at the reference voltage signal 549. The gain circuit 536 determines 604 a first reference voltage at the reference voltage signal 549 corresponding to a first test voltage at the test voltage signal 547, and a second reference voltage at the reference voltage signal 549 corresponding to a second test voltage at the test voltage signal 547. The gain circuit 536 calculates 606 the gain based on the first and second reference voltages and the first and second test voltages.

FIG. 7 is a high speed communication system that includes a receiver 700, according to yet another embodiment. The receiver 700 illustrated in FIG. 7 is similar to the receiver 100 illustrated in FIG. 1. The main difference is that the receiver 700 includes another summing preamp circuit 706 and another data decision circuit 712, and the controller 120 includes a MUX 702. As a result, there are two data decision paths: a main data decision path (706 and 712) and an adaptive data decision path (106 and 112).

The receiver 700 can operate in two modes: a calibration mode and a normal operating mode. In the calibration mode, the linearization circuit 132 generates different nonlinear preamp code mappings for the summing preamp circuit 706

and the summing preamp circuit 106, respectively. For example, the linearization circuit 132 generates a first nonlinear preamp code mapping correcting for nonlinear characteristics of summing preamp circuit 706, and a second nonlinear preamp code mapping correcting for nonlinear characteristics of the summing preamp circuit 106. The nonlinear preamp code mapping 134 includes the first and second nonlinear preamp code mappings.

The normal operating mode of the receiver 700 is similar to the normal operating mode of the receiver 100. The main difference is that while the main data path (706 and 712) is selected by the MUX 702, the adaptive data path (106 and 112) may be used to perform other real time calibration functions via circuitry not shown in FIG. 7, such as shifting a phase of the sampling clock 113 so that it is in the middle of a data eye. Similarly, adaptive data path may then be selected by the MUX 702 and the main data path may be used to perform other real time calibration functions such as clock phase shifting of sampling clock 713.

The summing preamp circuit 706 is the same as the summing preamp circuit 106. The summing preamp circuit 706 receives the analog input signal 105 from the AFE 104 and an input correction signal 741 from the controller 120, buffers the analog input signal 105, converts the input correction signal 741 into an analog signal, and then combines the buffered analog input signal and the converted input correction signal to generate a corrected input signal 711.

The data decision circuit 712 is the same as the data decision circuit 112. The data decision circuit 712 receives the corrected input signal 711 and makes a decision on the logical data value represented by the voltage of the corrected input signal 711. The data decision circuit 712 then generates an output data signal 715 that represents the data decision. The data decision circuit 712 is controlled by its own sampling clock 713.

The MUX 702 receives the output data signal 715 and the output data signal 115 and selects one of the output data signal 715 and the output data signal 115 for its output, selected signal 717. In the first calibration mode, the MUX 702 selects the output data signal 715, and in the second calibration mode, the MUX 702 selects the output data signal 115.

#### ADDITIONAL CONFIGURATION CONSIDERATIONS

In one embodiment, a representation of circuits within a receiving device may be stored as data in a non-transitory computer-readable medium (e.g. hard disk drive, flash drive, optical drive). These representations may in the form of, for example, behavioral level descriptions, register transfer level descriptions, logic component level descriptions, transistor level descriptions or layout geometry-level descriptions.

Throughout this specification, plural instances may implement components, operations, or structures described as a single instance. Although individual operations of one or more methods are illustrated and described as separate operations, one or more of the individual operations may be performed concurrently, and nothing requires that the operations be performed in the order illustrated. Structures and functionality presented as separate components in example configurations may be implemented as a combined structure or component. Similarly, structures and functionality presented as a single component may be implemented as

separate components. These and other variations, modifications, additions, and improvements fall within the scope of the subject matter herein.

As used herein any reference to “one embodiment” or “an embodiment” means that a particular element, feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. The appearances of the phrase “in one embodiment” in various places in the specification are not necessarily all referring to the same embodiment.

Some embodiments may be described using the expression “coupled” and “connected” along with their derivatives. For example, some embodiments may be described using the term “coupled” to indicate that two or more elements are in direct physical or electrical contact. The term “coupled,” however, may also mean that two or more elements are not in direct contact with each other, but yet still co-operate or interact with each other. The embodiments are not limited in this context.

As used herein, the terms “comprises,” “comprising,” “includes,” “including,” “has,” “having” or any other variation thereof, are intended to cover a non-exclusive inclusion. For example, a process, method, article, or apparatus that comprises a list of elements is not necessarily limited to only those elements but may include other elements not expressly listed or inherent to such process, method, article, or apparatus. Further, unless expressly stated to the contrary, “or” refers to an inclusive or and not to an exclusive or. For example, a condition A or B is satisfied by any one of the following: A is true (or present) and B is false (or not present), A is false (or not present) and B is true (or present), and both A and B are true (or present).

In addition, use of the “a” or “an” are employed to describe elements and components of the embodiments herein. This is done merely for convenience and to give a general sense of the disclosure. This description should be read to include one or at least one and the singular also includes the plural unless it is obvious that it is meant otherwise.

Upon reading this disclosure, those of skill in the art will appreciate still additional alternative structural and functional designs for a transmitter having a self-triggered transition equalizer through the disclosed principles herein. Thus, while particular embodiments and applications have been illustrated and described, it is to be understood that the disclosed embodiments are not limited to the precise construction and components disclosed herein. Various modifications, changes and variations, which will be apparent to those skilled in the art, may be made in the arrangement, operation and details of the method and apparatus disclosed herein without departing from the spirit and scope defined in the appended claims.

What is claimed is:

1. A receiver comprising:

a decision circuit to make a data decision based on an input signal of the decision circuit;

a summing preamp circuit to adjust the input signal of the decision circuit based on an input correction signal, the summing preamp circuit including a first preamp having nonlinear characteristics and a second preamp having linear characteristics;

a correction circuit to combine a plurality of signals corresponding to different input correction parameters into a preliminary input correction signal, an input of the correction circuit coupled to an output of the decision circuit; and

a control circuit to map the preliminary input correction signal into the input correction signal using a nonlinear code mapping, wherein the nonlinear code mapping corrects for the nonlinear characteristics of the first preamp.

2. The receiver of claim 1, wherein the signals corresponding to different input correction parameters comprise: an offset correction signal corresponding to a voltage offset between positive and negative inputs of the decision circuit;

an adaptation target signal corresponding to an adaptation threshold for adaptation of one or more receiver coefficients; and

a decision feedback equalizer (DFE) tap signal.

3. The receiver of claim 1, wherein the summing preamp circuit further includes a summing circuit,

wherein the first preamp receives the input correction signal and converts the input correction signal to generate an analog correction signal,

wherein the second preamp receives an input signal of the summing preamp circuit and buffers the input signal to generate a buffered signal, and

wherein the summing circuit combines the analog correction signal and the buffered signal to generate the input signal to the decision circuit.

4. The receiver of claim 1, further comprising:

a comparator circuit to compare the input signal of the decision circuit to a reference voltage;

circuitry to determine a first voltage level of the reference voltage corresponding to a first test voltage and a second voltage level of the reference voltage corresponding to a second test voltage based on an output of the comparator circuit; and

circuitry to calculate a receiver gain based on the first voltage level of the reference voltage, the first test voltage, the second voltage level of the reference voltage and the second test voltage.

5. The receiver of claim 4, wherein the circuitry to calculate the receiver gain calculates the receiver gain based on a quotient of a difference of the first voltage level of the reference voltage and the second voltage level of the reference voltage, and the first test voltage and the second test voltage.

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